Evaluating VDL Mode 2 Performance Through Simulation

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Project Overview

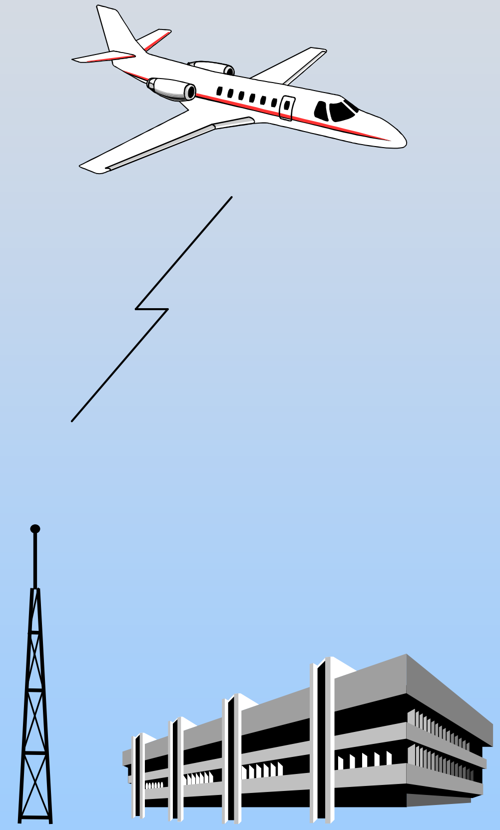
• Funded by the Advanced Communications for Air Traffic Management project at NASA. The AC/ATM project is tasked with researching systems to provide the improved performance and increased capacity required for future air traffic management concepts.

• Objective: To study the characteristics of the VDL Mode 2 data link and determine through simulation the expected performance and capacity in an ATN scenario.

• Work in progress. Current focus is on a single VDL Mode 2 subnet.

VDL Mode 2 Overview

- VHF Digital Link (VDL) for communication between aircraft and ground stations
- Selected for Controller Pilot Data Link Communication (CPDLC) Build 1 and 1A in US
- Data Link and Physical layer specifications
- Use the Aeronautical VHF Band (118 - 137 MHz)
- D8PSK modulation, 31.5 kbps data rate
- Medium access by CSMA



VDL Sublayers

A VDL system consists of several sublayers:

VDL Management Entity (VME)

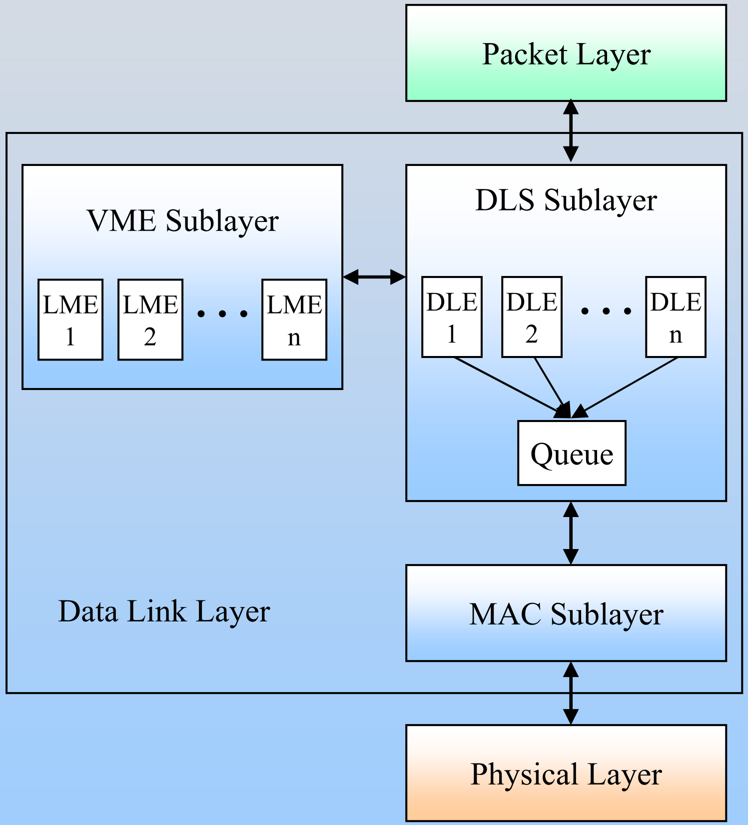
Responsible for connection establishment and handoffs. Creates a Link Management Entity (LME) for each connection.

Data Link Service (DLS)

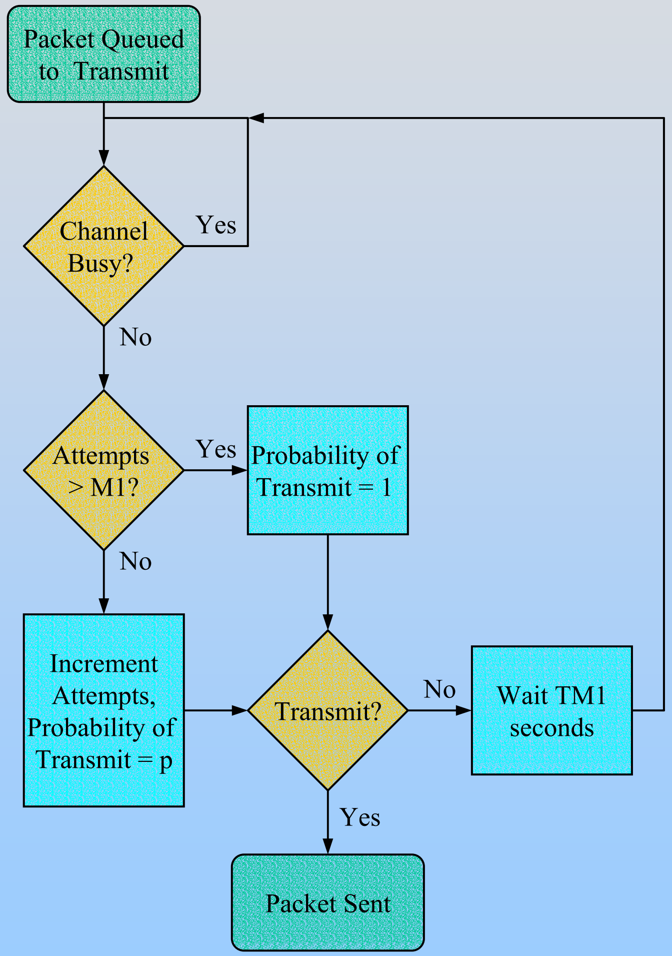
Manages data communication between the aircraft and ground station, providing the addressing and controlling link usage. Maintains a Data Link Entity (DLE) for each connection. The DLEs use the Aviation VHF Link Control protocol (AVLC).

Medium Access Control (MAC)

Responsible for determining when access to the link can be granted. Uses a Carrier-Sense Multiple Access (CSMA) protocol.



MAC Sublayer



Carrier Sense Multiple Access (CSMA)

- limited p-persistent
  - Attempts to minimize collisions and access delay
- fixed backoff

Name	Description	Default
M1	Max. access attempts	135
p	Persistence	13/256
TM1	Inter-access delay timer	4.5 ms
TM2	Channel busy timer	60 s

MAC Sublayer Parameters

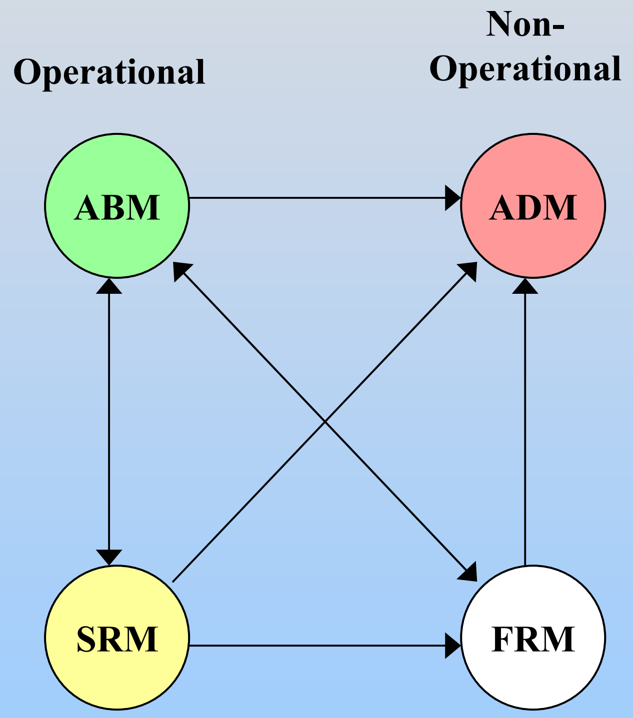
DLS Sublayer

Provides addressing and error detection

- Manages a DLE for each air-ground connection
  - DLEs use the AVLC protocol
- Maintains an active 2-level queue
  - Link control frames sent in preference to data
  - Redundant frames are eliminated
  - Acknowledgements are updated
  - Acknowledged frames are removed

AVLC Protocol

- AVLC – Aviation VHF Link Control
- Point-to-point protocol
- Operates in the Asynchronous Balanced Mode (ABM)
  - Aircraft and Ground Station act as peers
  - Communications can be initiated by either side
- Sliding window
  - Default size: 4 frames
- Selective Reject
  - Can reject and acknowledge individual frames
- Retransmission time-out value is dynamic
  - Link utilization
  - Maximum retransmission count
  - Using default parameters, 2.2 s minimum



Modeling VDL

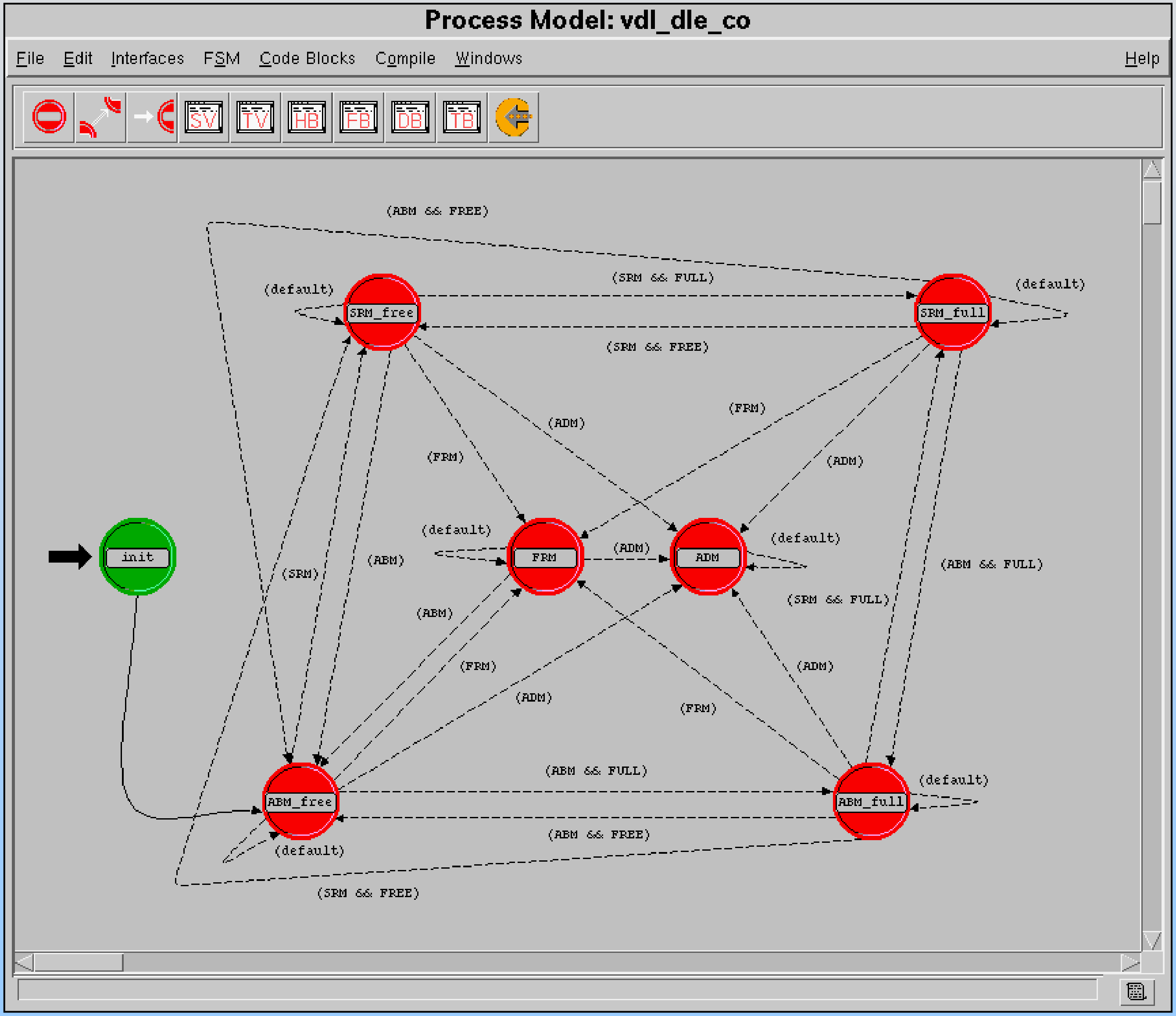
Simulations created in OPNET Modeler

- Current release 9.0.A

Components:

- Process Models
    - Models a specific protocol or function
- Node Models
    - Group of protocols
    - Models a device
- Simulation Scenario
    - Combines models for nodes, links, radio channels, etc.

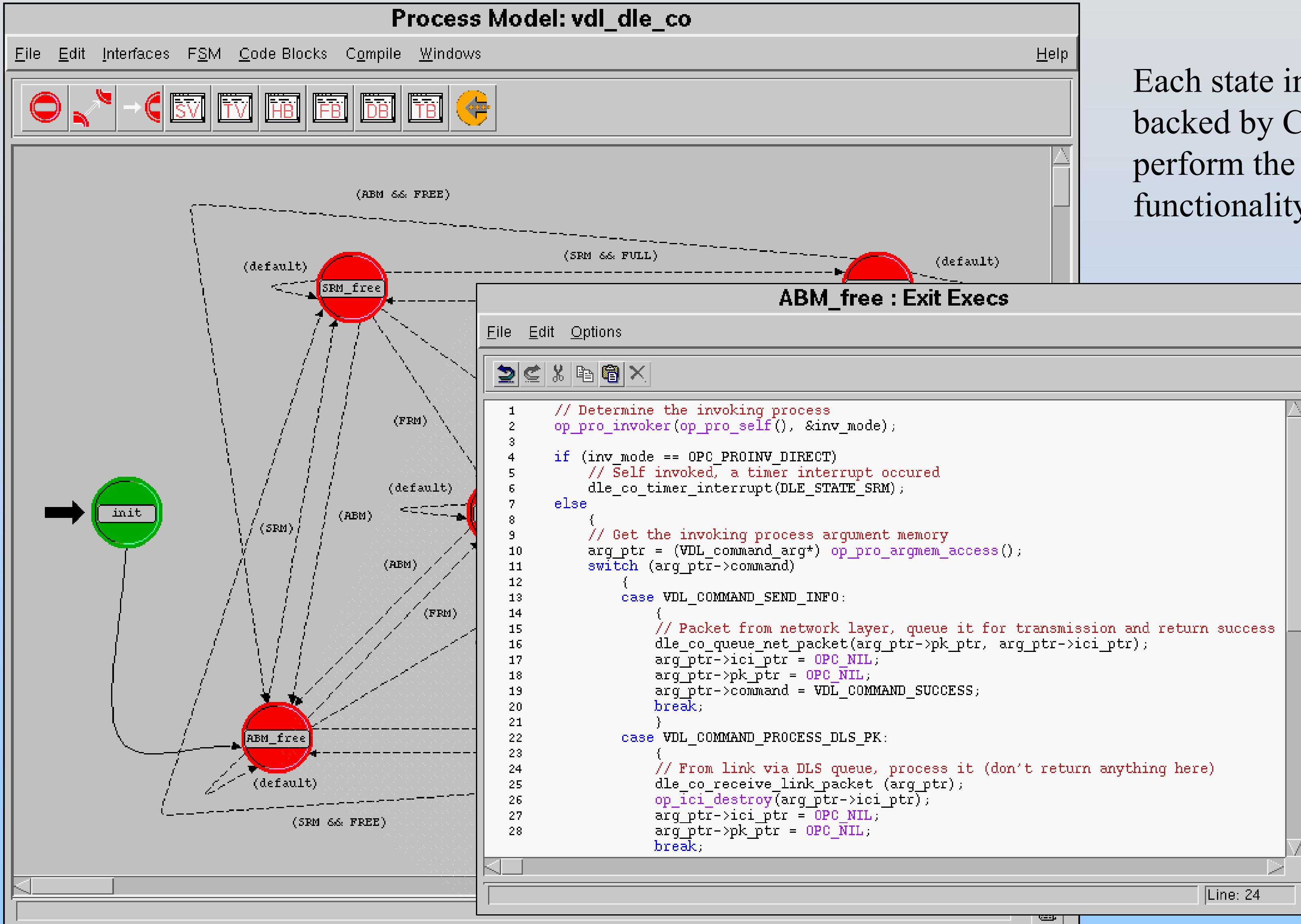
Process Models



Each VDL protocol is designed as a finite state machine. State transitions are the result of interrupts, such as packet reception or timer expiration.

AVLC process model is shown.

Process Models



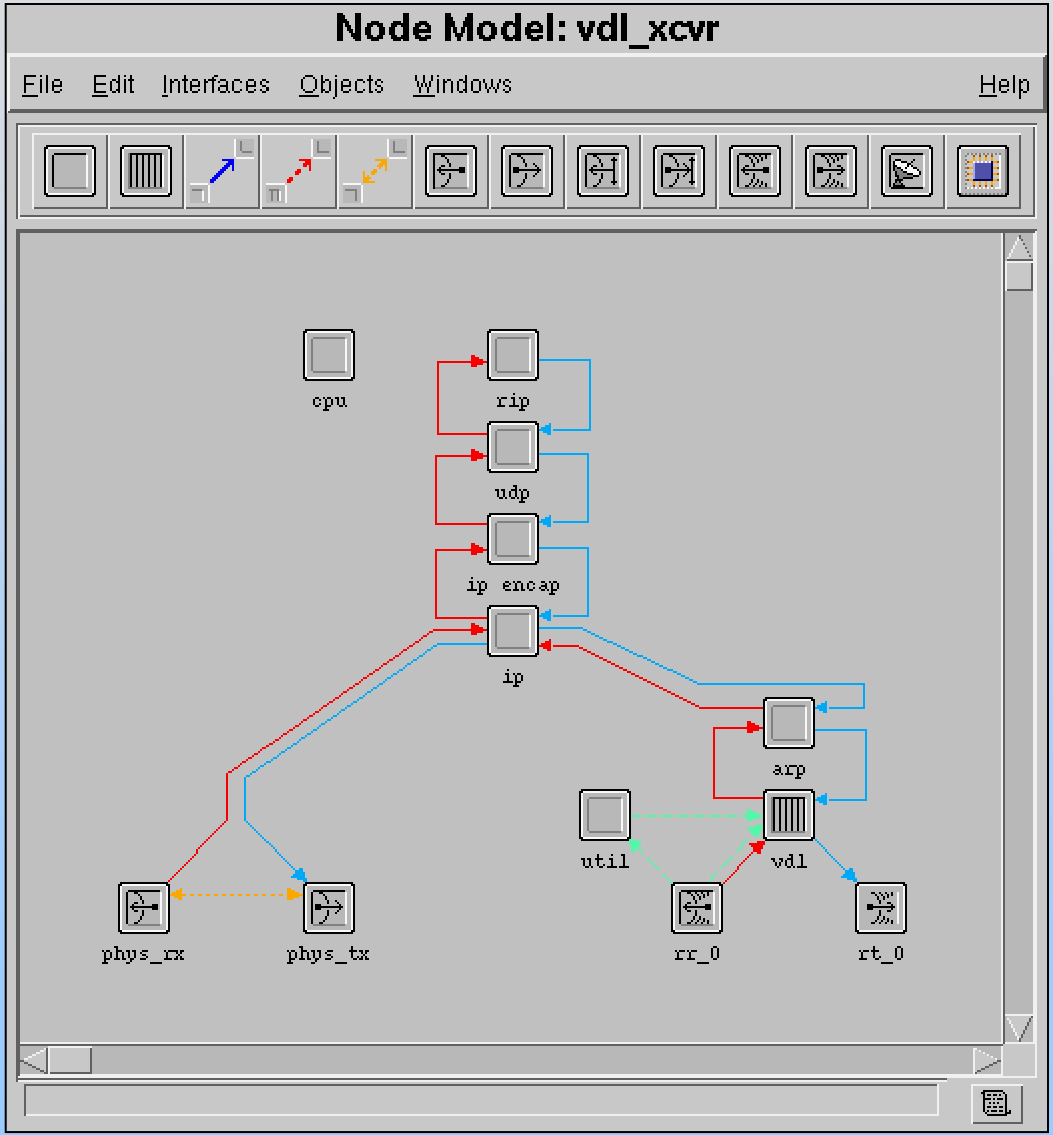
Each state in the FSM is backed by C code to perform the protocol functionality.

Node Models

Processes are linked together into a node model, where each block represents a process model. Node models represent devices.

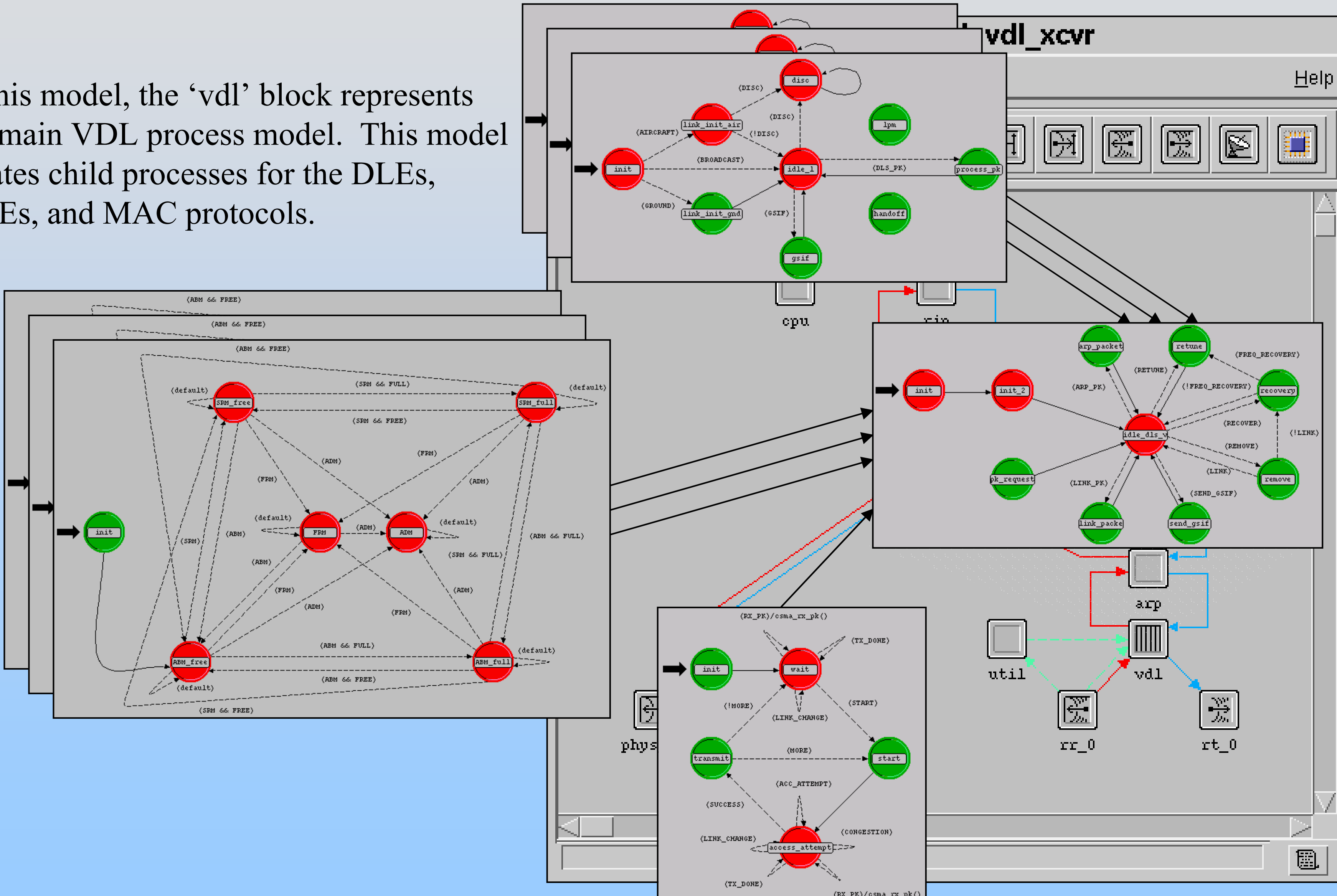
Processes are connected together with packet streams and statistic wires that define the communication paths between protocols.

This model represents a combined ATN air/ground router and a VDL VHF Digital Radio (VDR)

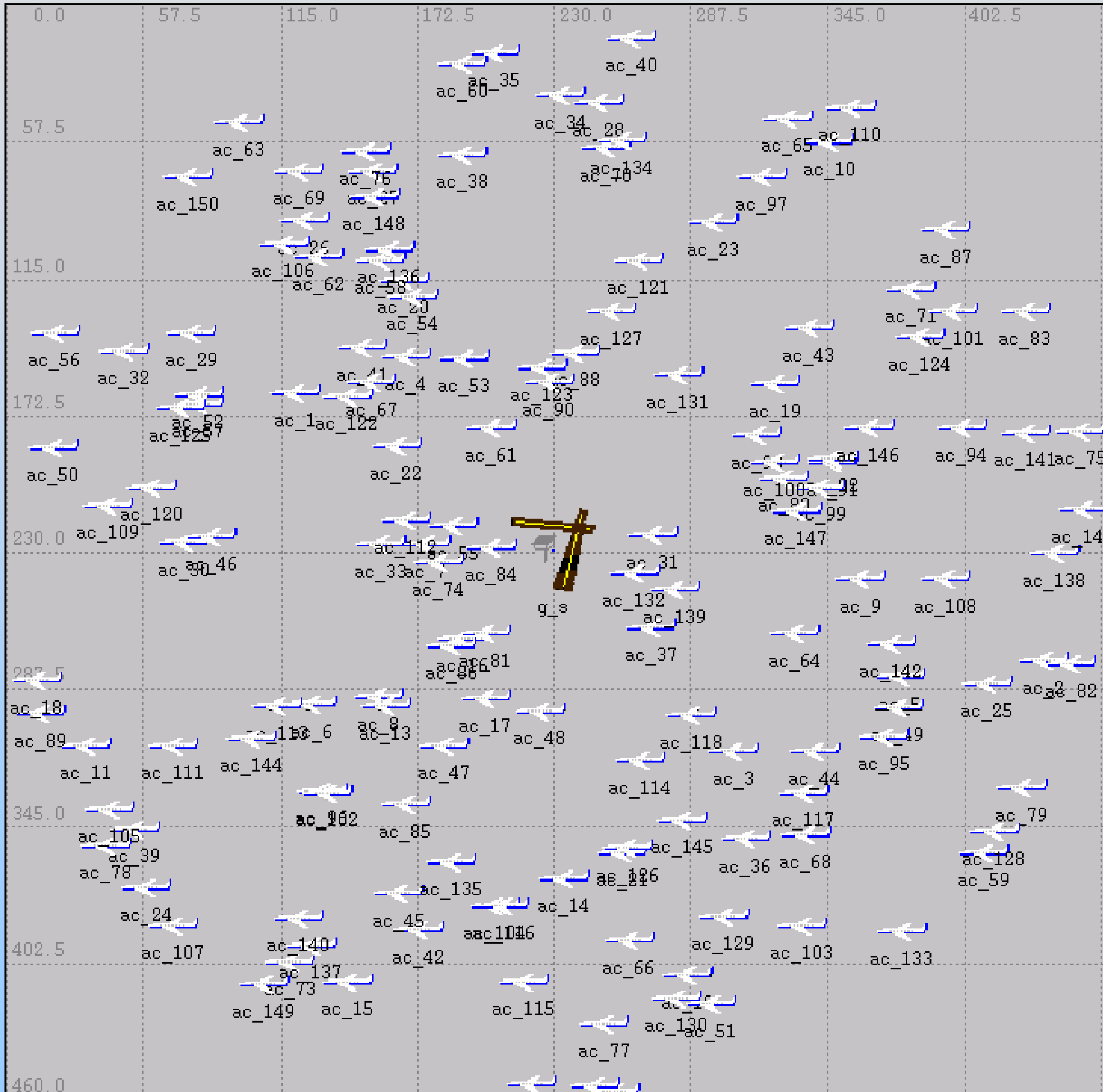


Node Models

In this model, the ‘vdl’ block represents the main VDL process model. This model creates child processes for the DLEs, LMEs, and MAC protocols.



Simulation Scenario



- Up to 150 aircraft randomly located within 200 nautical miles of the ground station
- Each aircraft is fixed at an altitude of 30,000 feet.
- Each simulation lasted for a period of 1 hour, in which all the aircraft were in continuous contact with the ground station.
- All default parameters used except as noted

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Simulation Scenario

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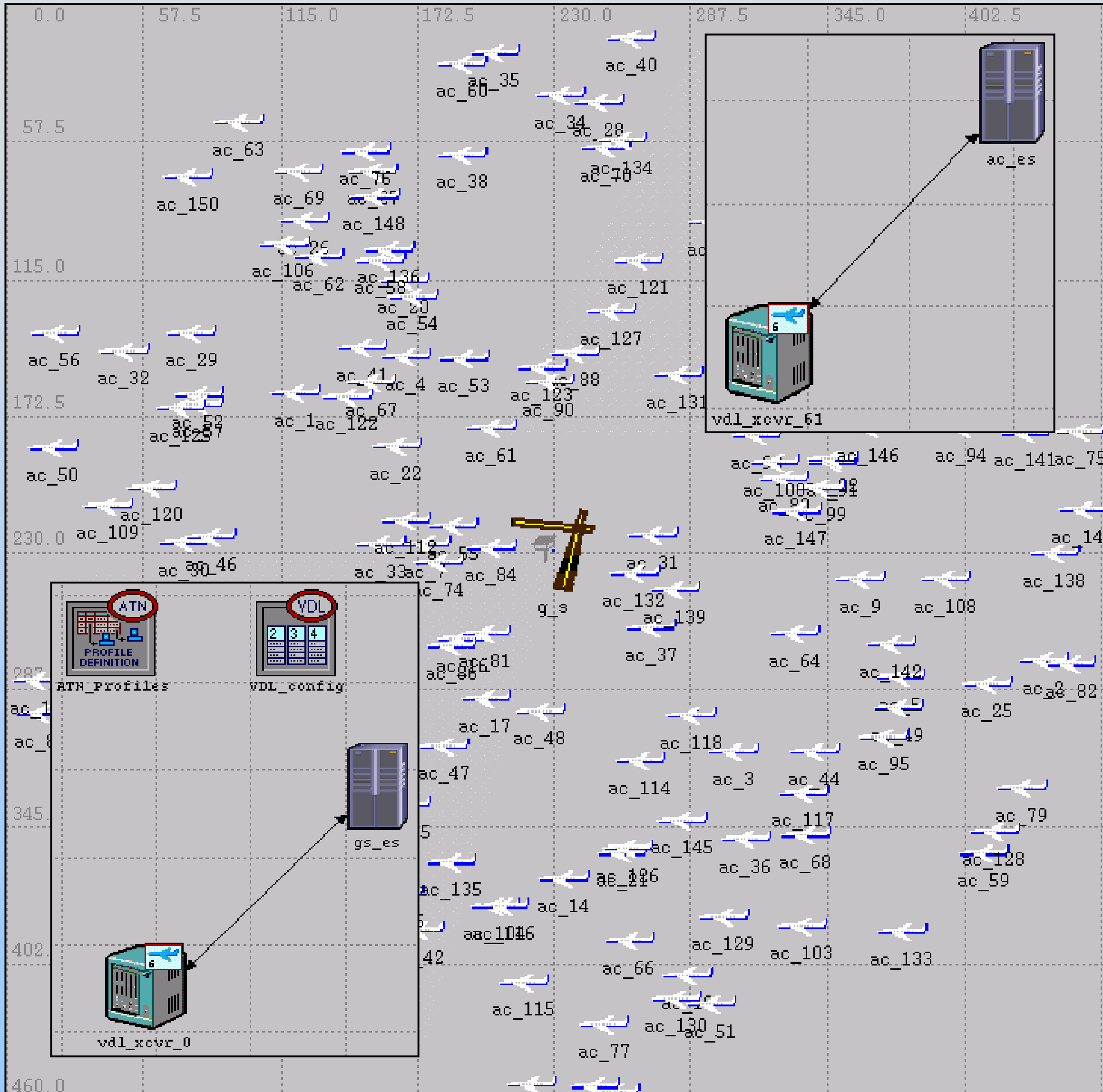


- Subnets are simplified, containing an ATN router/VDR and an end system
  - Ground network not modeled
  - Aircraft network not modeled
- Fixed network – dynamic routing protocol not required
  - Static routing tables used

Traffic Profile

- Terminal domain traffic for the year 2015
- Includes Air Traffic Service (ATS) and Aeronautical Operational Communications (AOC) messages
- Adopted by AMCP WG-D / RTCA SC-172
- Parameters defined in table correspond to a Load Factor (LF) of 1.0

Priority	Uplink		Downlink		Message Rate Dist.	Message Size Dist.
	Mean Rate (message/s)	Mean Size (bits)	Mean Rate (message/s)	Mean Size (bits)		
High	0.017	137	0.024	110	Exponential	Poisson
Medium	0.0017	198	0.0008	100		
Low	0.001	2400	0.002	2400		
Low[1]	0.017	3325	0.0033	1760	Constant	Constant

1. Low constant uplink messages are broadcast

Persistence

Using a load factor of 1:

• Mean downlink message rate (per aircraft)

~ 0.03 messages/sec

• Mean uplink message rate (per ground station)

~ 0.02 messages/sec/aircraft + .017 messages/sec

• With 90 aircraft, mean uplink message rate ~1.8 messages/sec

• Ground generating more messages while competing for link on equal basis with aircraft leads to growing queuing delays – B. Hung

⟹ Increase ground persistence to compensate

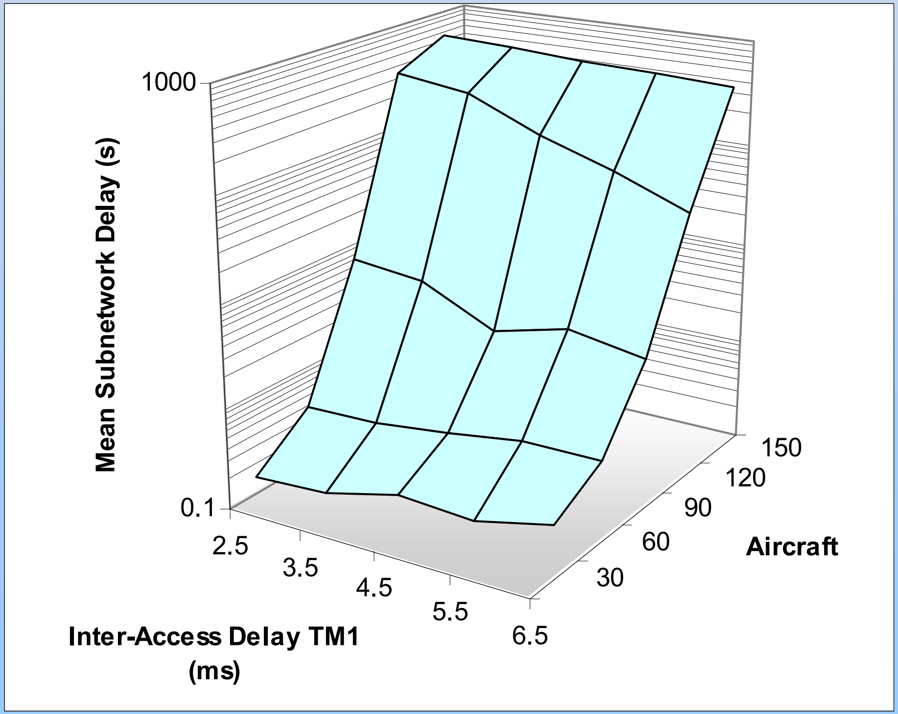
Initial Simulations

- Used IP stack in simulations in place of the specified CLNP/TP4 protocols
  - Reason: IP models available in OPNET
  - IP and CLNP have similar functionality
- Email protocol over UDP used to create traffic flow
  - The 16-byte response packet represents a TP4 acknowledgement
- Broadcast not supported for application data
  - Approximated by sending broadcast data as point-to-point to a single destination
- Ran VDL Mode 2 simulations with 2 separate traffic profiles
- Traffic profiles used a LF of 1

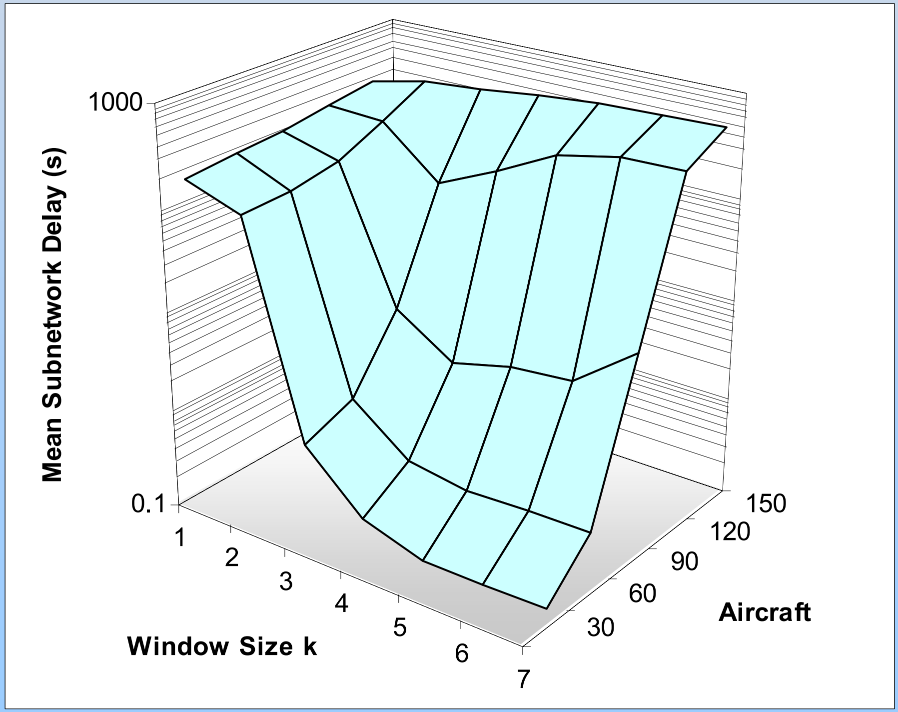
Parameters

- Optimal inter-access delay TM1 is dependent on the number of aircraft
- TM1 should increase as number of aircraft increases.

- Optimal AVLC window size is dependent on the number of aircraft
- Window size should decrease as number of aircraft increases.



Varied TM1, all other parameters default



Varied k, all other parameters default

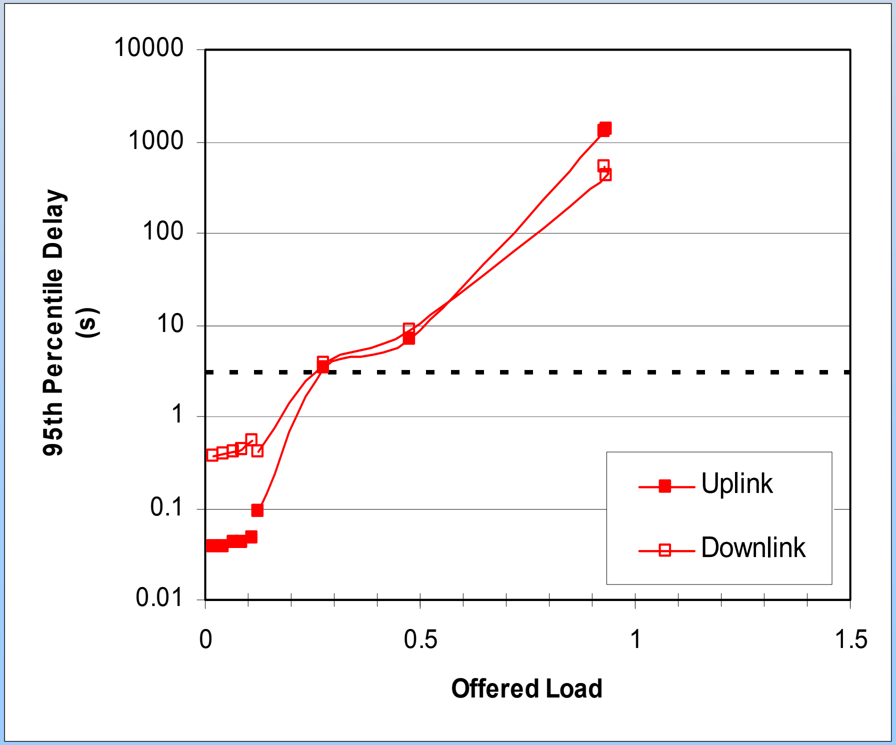
Subnetwork Delay

Simulation with ground p = 156/256

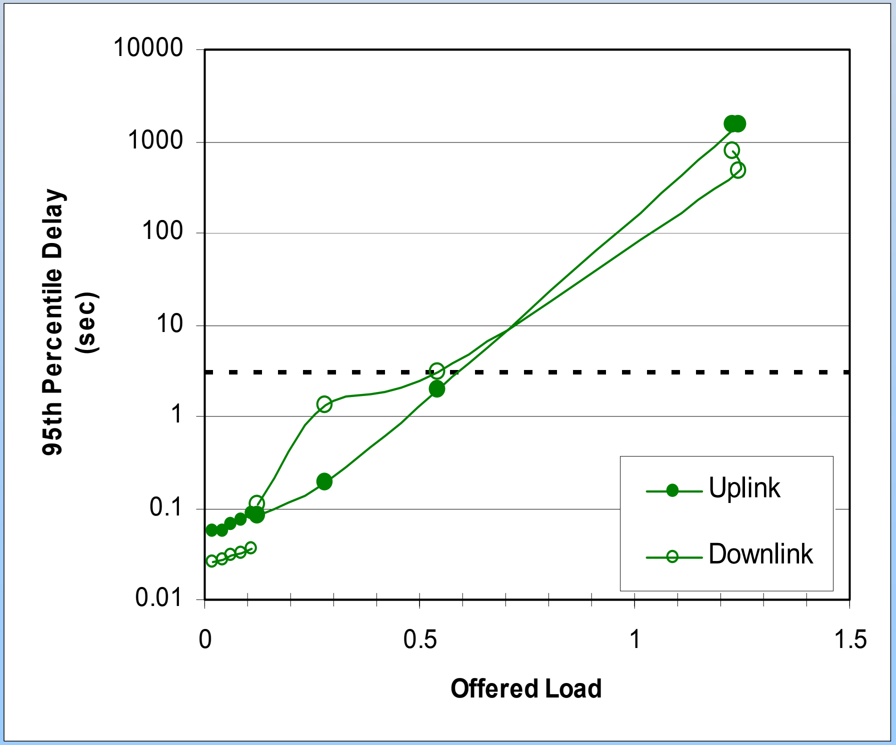
- 3-second 95th percentile subnetwork delay exceeded at an offered load of 0.27
- Capacity is approximately 60 aircraft

Optimized simulation for 90 aircraft, with ground p = 90/256 and TM1 = 0.5 ms

- 3-second 95th percentile subnetwork delay exceeded at an offered load of 0.52
- Capacity is approximately 90 aircraft



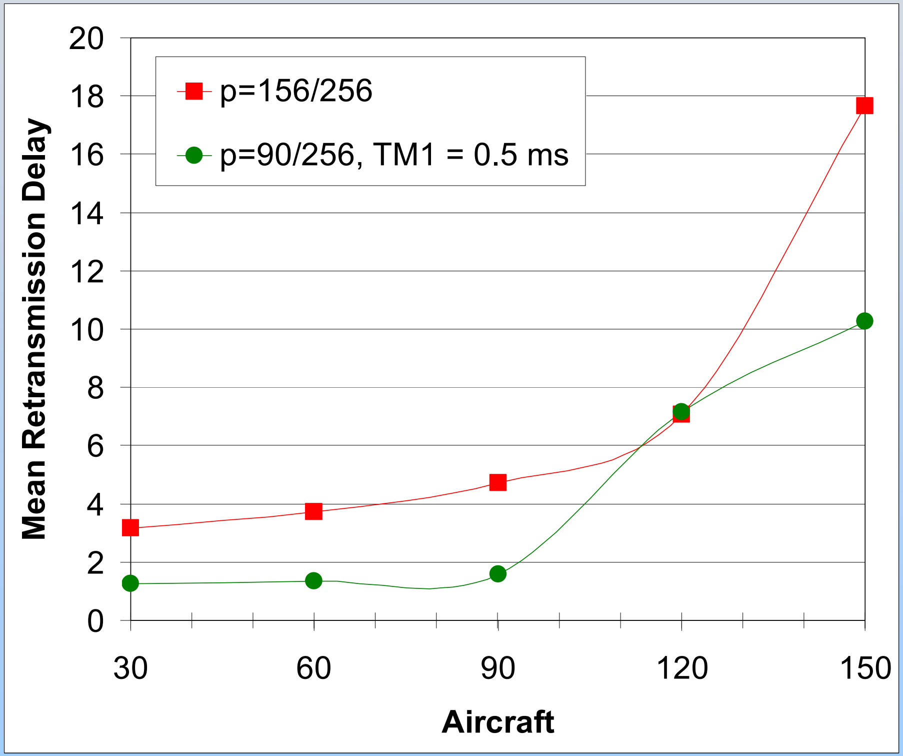
Ground p = 156/256



Ground p = 90/256, TM1 = 0.5 ms

Retransmission Delay

- TM1 is part of the 99th percentile transmission delay estimate for calculating the retransmission delay
- With up to 90 aircraft, reducing TM1 from 4.5 to 0.5 ms lessened the retransmission delay by at least 2 seconds
- Retransmission delay at least 3 seconds with TM1 = 4.5 ms, less than 2 seconds with TM1 = 0.5 ms
- Possible contributor for the reduced 95th percentile subnetwork delay and greater capacity

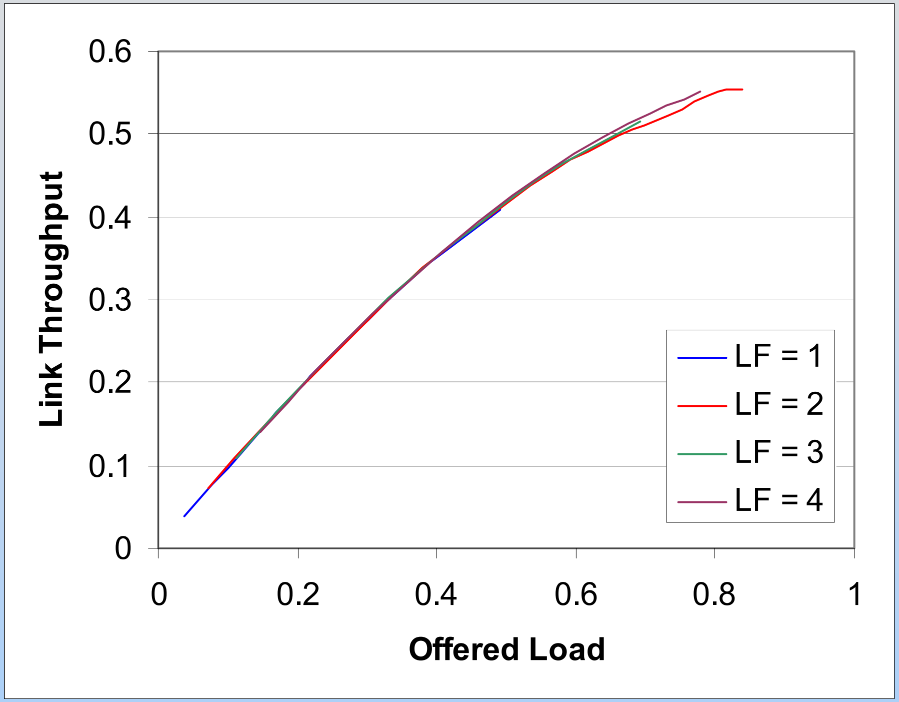


Ground p and TM1 modified, all other parameters default

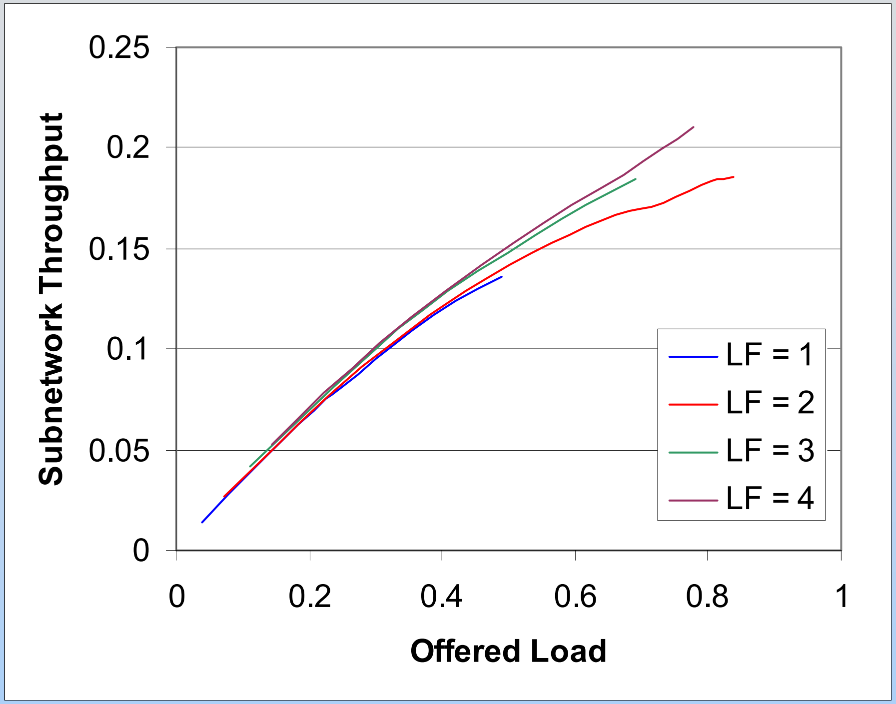
Refinements

- Custom application process created to better model the traffic flows
  - Runs over connection-less transport protocol
  - A 34-byte response packet is sent to simulate the TP4 acknowledgment
- Representative IDRP update messages added to simulations
- IP stack still used
  - An intermediate process designed to provide address resolution modified to also adjust for IP and CLNP header size discrepancies.
  - Same process also models the compression function specified for mobile links
- Broadcast support added for applications
- Traffic varied from LF of 1 to 4

Throughput



Ground p = 90/256



Ground p = 90/256

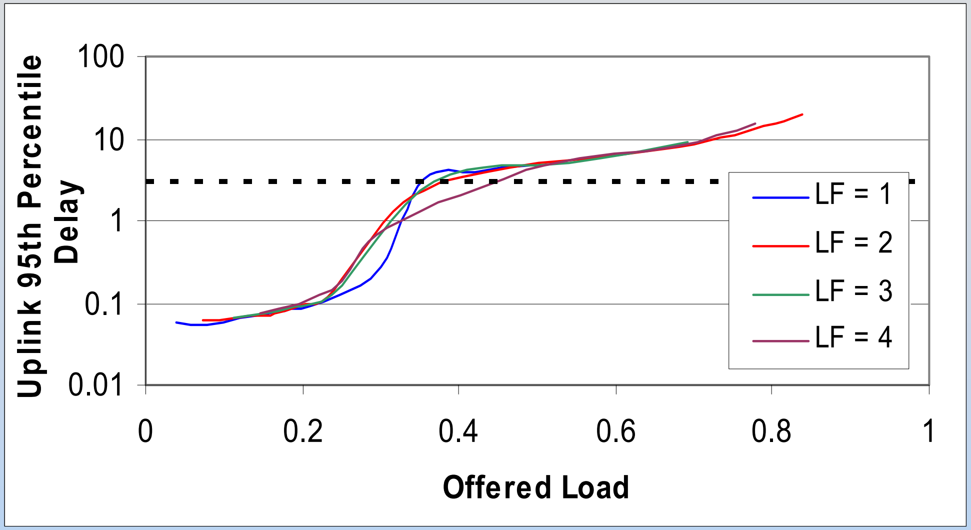
Link Throughput

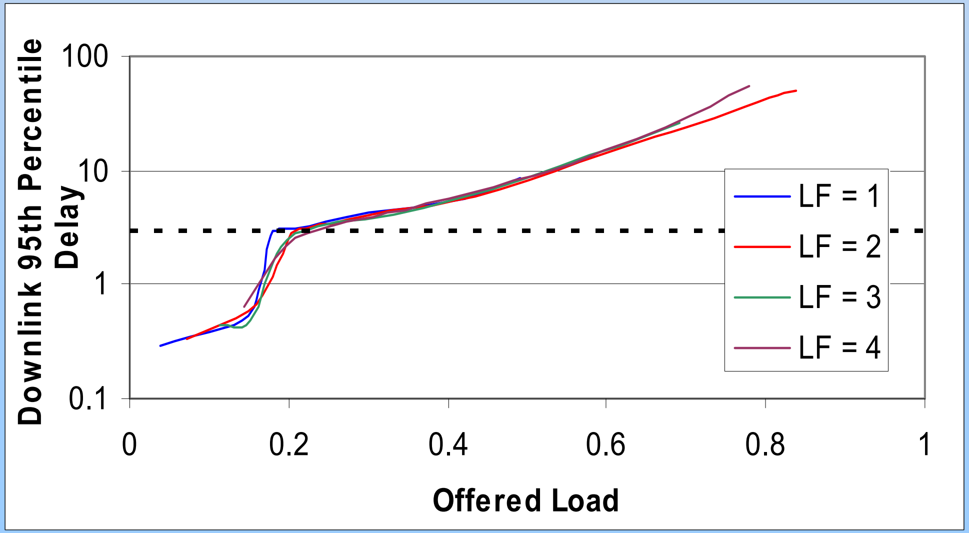
- Includes all overhead
- Independent of number of aircraft
- Peak throughput not obtained in sims

Subnetwork Throughput

- Does not include VDL overhead
- Much lower than link throughput
- Affected by number of aircraft

Delay





Ground p = 90/256

95th percentile subnetwork delays

- FAA limit – 3 seconds in terminal domain
- Uplink limit reached at offered load of 0.35
- Downlink limit at offered load of 0.2

Load Factor	Max Aircraft
1	65
2	40
3	25
4	20

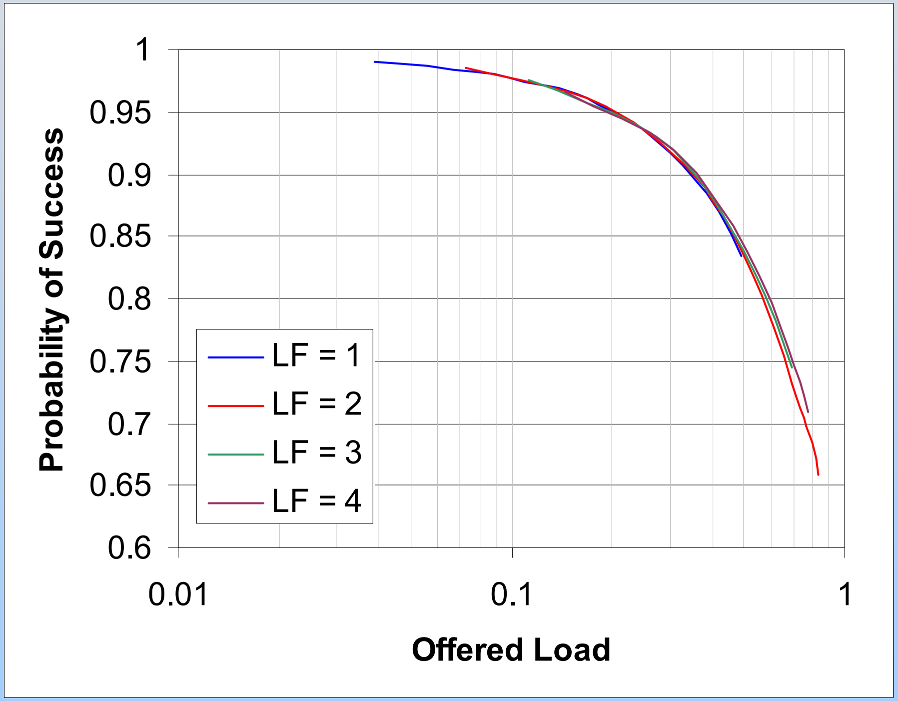
Max aircraft for Load Factor

Delay / Retransmission

- 95^{th} percentile delay based on queuing, channel access, transmission, and propagation delays when retransmission rate less than 5%
- Retransmission delay included in 95^{th} percentile delay when retransmission rate exceeds 5%
- Probability of success: 0.95 at offered load 0.2

  ~ 5% of frames retransmitted at least once
- 95th percentile delay limit at offered load 0.2
- 3-second 95^{th} percentile delay limit reached when retransmission delay

  ══► retransmitted frames have a subnetwork delay of at least 3 seconds



Ground p = 90/256

Persistence Revisited

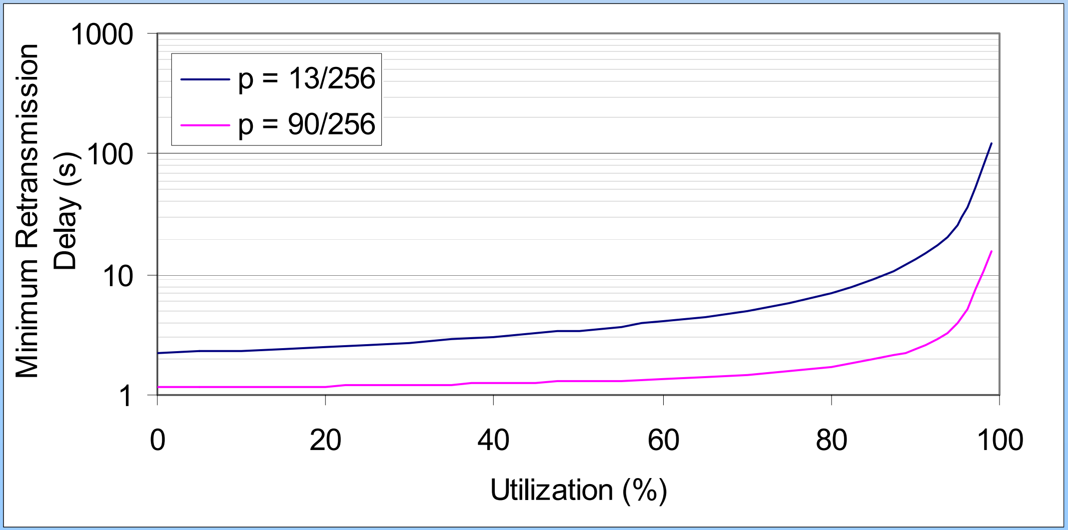
- M1 chosen such that the probability that the MAC will not transmit M1 times in a row is less than 0.1% ⟹ $(1 - p)^{M1} = 0.001$

- M1 affects the retransmission delay. If aircraft p ≠ ground p and M1 is matched to p, the retransmission delays calculated by the aircraft and the ground will differ.

- Using aircraft p = 13/256 and M1 = 135, and the ground p = 90/256 and M1 = 16, the ground retransmission delay is much lower than the aircraft.

  - undesirable, uplink delays already lower in simulations

- Ideally, the uplink and downlink retransmission delays should be the same.



Conclusions

• For maximum capacity, subnetwork parameters should be optimized for the number of aircraft in system and adjusted as appropriate when that number changes

- Ground can use a Link Parameter Modification command
- Parameters must be carefully chosen, as they will affect several performance metrics including subnetwork delay and maximum throughput

• AVLC retransmissions, and their associated delays, are what limits the system for the 3-second 95th percentile delay requirement

- Reducing the retransmission delay could lead to higher capacity

• Using different persistence values in the ground and aircraft is necessary to achieve maximum capacity, although VDL Mode 2 as defined in standard not intended for this.

Acknowledgment

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